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DIVERS SOLAR ROTATIONS

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The subject of solar rotation, or more properly rotations, has become of considerable interest in the last few years. These new developments are primarily associated with spacecraft observations, including observations of the interplanetary medium near the earth, and with improved ground-based solar telescopes and digital data-handling facilities. The physical processes responsible for these divers observed solar rotations and the relationships between them are by no means understood, but may perhaps serve as an interesting challenge to the participants in this conference.

If one looks in a modern textbook on solar physics under rotation one will find the classical results of Newton and Nunn (1951) as shown by the solid curve in Figure 1. They studied the rotation periods of long-lived sunspots which could still be observed when they returned to the visible solar disk one rotation later. In order to acquire enough statistics to reasonably well define a differential rotation curve it was necessary to combine the observations during a complete 11-year sunspot cycle, or at the very least during perhaps half of a cycle. We shall see later that in modern observations this time period necessary to define a differential rotation curve can be reduced from eleven years to one hour, with some interesting consequences resulting. Newton and Nunn found that the differential rotation of the long-lived sunspots was essentially unchanged during several 11-year sunspot cycles.

Sunspots mark the location of small-scale strong magnetic fields having a magnitude of a few kilogauss. By contrast we may inquire about the rotational properties of the large-scale weak

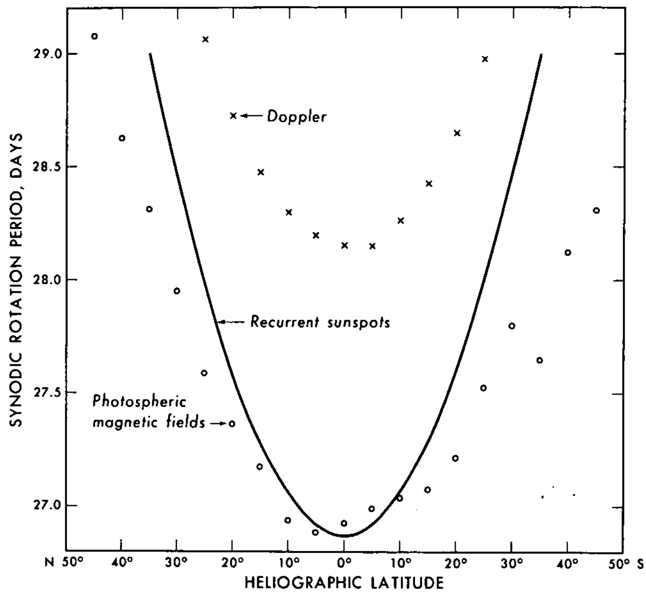

Fig. 1. Solar differential rotation. The solid curve represents the results of Newton and Nunn (1951) for long-lived sunspots. The circles are the average results for large-scale photospheric magnetic fields. The X's are average results obtained by Howard and Harvey (1970) from Doppler observations, with the results from the northern and southern hemisphere observations shown separately (from Wilcox and Howard, 1970).

photospheric magnetic fields whose magnitude is a few gauss. This question was investigated using autocorrelation techniques by Wilcox and Howard (1970) with the results shown by the circles in Figure 1. We see that near the equator the rotation period of the large-scale field is approximately the same as the sunspots, but at higher latitudes the period of the large-scale field becomes slightly less than the period of the sunspots. In the autocorrelation analysis of the periods of the large-scale photospheric field it was necessary to use observations during an interval of approximately six months in order to define a statistically significant differential rotation curve. This is an improvement from the eleven years required for the analysis of the rotation of long-lived sunspots, and we find from one 6-months interval to another a considerable variation in the rotation properties of the field (the results shown in Figure 1 represent an average over several years). During some 6-month intervals the range of latitudes within perhaps 20° of the equator may show an almost rigid rotation.

Since interactions between magnetic fields and plasmas lie at the heart of cosmical plasma physics, we may inquire about the rotational properties of the photospheric plasma. The line-of-sight component of the plasma velocity is observed from the Doppler shifts of Fraunhofer absorption lines. The most recent and comprehensive results have been given by Howard and Harvey (1970) using daily observations of Doppler shifts over the entire solar disk obtained simultaneously with the observations for the daily solar magnetograms at Mount Wilson Observatory. These results are shown as X's in Figure 1. We notice immediately the startling result that the average period of the plasma rotation is approximately $1\frac{1}{4}$ days longer at each latitude than the period of the magnetic fields. If we take these observations literally this means that on the average the photospheric field lines have a rotational velocity about 4 or 5% larger than the photospheric plasma, or that the field lines are plowing through the plasma with a relative velocity of about 100 m/sec. This is surprising since on the large scale we would expect the field to be frozen into the plasma. A beginning toward a physical explanation of this result may be found in the observations of Sheeley (1967) that many of the photospheric field lines do not exist as a relatively uniform large-scale field but instead are clumped into small filaments of cross-section less than 500 kilometers and with field strengths of the order of a kilogauss. Within these filaments the magnetic energy density $B^2/8\pi$ is larger than the plasma energy density.

The time interval required to obtain a complete differential rotation observation from the Doppler shifts is approximately the one hour required to obtain a solar magnetogram. This time is to be compared with the six months required for the autocorrelation analysis of the large-scale magnetic fields, and with the eleven years required for observations of long-lived sunspots. The large improvement comes from the greatly increased number of observations that can be obtained with the solar magnetograph across the entire visible disk during the course of one hour, and is possible only because of modern digital data-handling capabilities. These observations are usually obtained once per day. The variation in the differential rotation which we have already encountered in the above discussion now becomes very large, as is graphically illustrated in a motion picture prepared from the Doppler observations of Howard and Harvey (1970). One frame from this movie is shown in Figure 2. If this figure were the motion picture we would see the lines representing the observations in continual motion from day to day, often deviating from the average curve by 10 or 15%. The observed curve will often be above the average for perhaps half a dozen days, and then below the observed curve for a similar interval. There does not appear to be a precise periodicity associated with these changes.

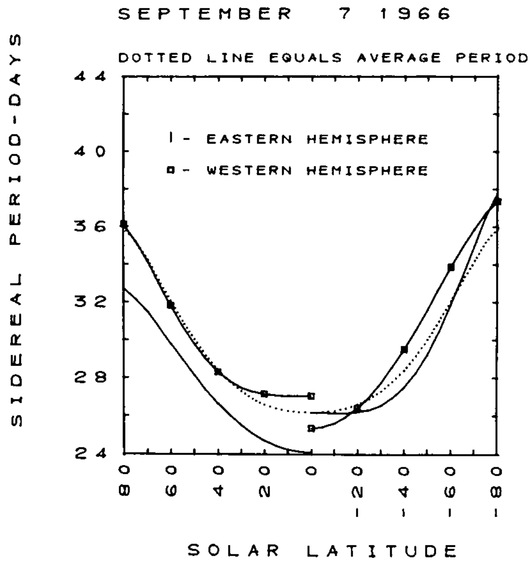

Fig. 2. Sample frame from motion picture representing Doppler shift observations of Howard and Harvey (1970). The results for the eastern half of the visible solar disk and for the western half are shown separately.

Very recent work by Gosling and Bame (1971) suggests that a similar difference between the field and the plasma rotation periods may exist in the interplanetary medium observed by spacecraft near the earth. The variation of the recurrence period of the solar wind plasma during an interval of several years is shown in Figure 3. We note that there is considerable variation in this quantity, just as was the case for the observations of the recurrence period of the photospheric plasma. We should note an important distinction between the two observations. In the case of the line-of-sight Doppler observations of the photospheric plasma we are observing and analyzing an actual rotational component of plasma velocity. In the case of the observations of the solar wind plasma we are doing an autocorrelation of the solar wind velocity, which velocity is predominantly directed in the radial direction away from the sun. Thus the recurrence peak in the autocorrelation is not the result of a rotational component in the solar wind plasma velocity, but rather represents the return of features in the solar wind velocity. Probably the predominant contribution to the recurrence peak comes from the recurring streams of high velocity solar wind plasma. Each of these streams tends to be observed for a few days, corresponding to a longitudinal width of perhaps 50 to 100 degrees.

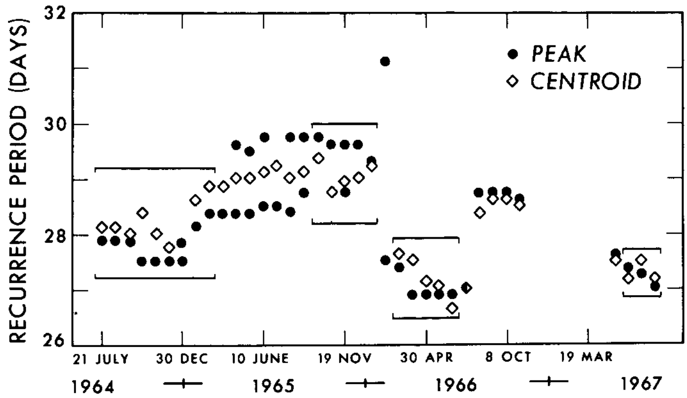

Fig. 3. Estimates of the period of recurrence of stationary solar wind velocity structures. The brackets enclose the most reliable determinations of recurrence period. PEAK and CENTROID refer to the autocorrelation curves from which these periods were estimated (from Gosling and Bame, 1971).

We may contrast the recurrence period of the solar wind velocity shown in Figure 3 with the recurrence period of the interplanetary magnetic field observed by Wilcox and Colburn (1970) and shown in Figure 4, which is also determined with autocorrelation techniques. There is a considerable tendency in the interplanetary medium for the recurrence period of the plasma to be several percent longer than the period of the field, just as was the case in the photosphere as shown in Figure 1.

With direct month-by-month comparisons of the variations in the recurrence periods of the photospheric plasma and of the solar wind plasma it may be possible to investigate the relationships between these quantities and to begin to get an idea of the physical processes involved. Some authors have discussed the large-scale (i.e. several days) variations in the solar wind velocity in terms of channeling effects in the strong magnetic fields of the chromosphere and low corona. To the extent that the recurrence periods of the photospheric and the solar wind plasma may be related as discussed above, and noting that the recurrence period of the magnetic fields tends to be distinctly shorter than the plasma periods, it appears that the most important physical influence on the large-scale solar wind velocity may rotate with the photospheric plasma, not with the fields.

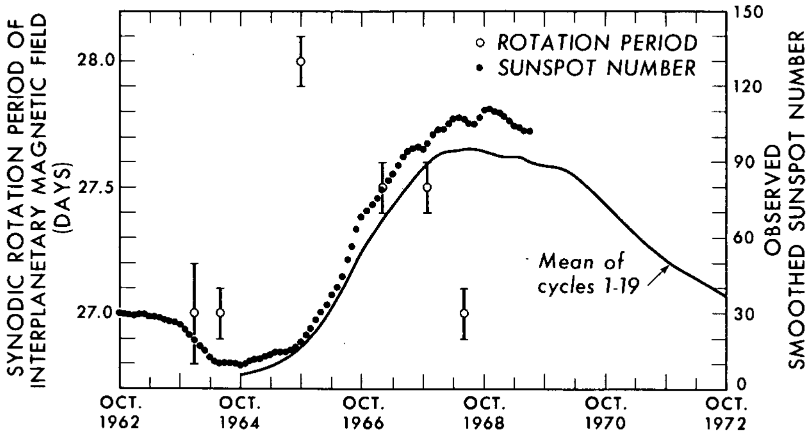

Fig. 4. The synodic rotation period of the interplanetary magnetic field and the observed sunspot numbers during the past several years (from Wilcox and Colburn, 1970).

At a height in the solar atmosphere in between the photosphere and the interplanetary medium near one AU that we have just discussed, namely the chromosphere and the lowest corona, Livingston (1971) has apparently observed a super rotation of the tenuous plasma that surrounds the localized features of strong magnetic field such as the prominences. In these observations the slit of a spectrograph is set perpendicular to the solar limb at the location of a prominence, and the Doppler shift is observed as a function of height above the solar limb. From the limb up to near the top of the prominence the observed wavelength is nearly constant. Presumably within this range of heights the strong magnetic fields associated with the prominence are rooted in the photosphere and cause the dense prominence material to corotate with the photosphere. Above the top there is a considerable change. Wisps of material appear to have Doppler shifts corresponding to an increased rotational velocity 10 or 20% larger than the photospheric value. This may correspond to tenuous plasma super-rotating above the region where the strong magnetic field enforces corotation.

Finally we may discuss the rotation properties of the recently discovered solar sector structure (Wilcox and Howard, 1968), which has been discovered by comparing spacecraft observations of the nearby interplanetary magnetic field with observations of the photospheric magnetic field obtained with the solar magnetograph at Mount Wilson Observatory. Unlike the other solar observations discussed above, the sector structure appears to rotate in a rigidly rotating system with a synodic period near 27 days. A schematic

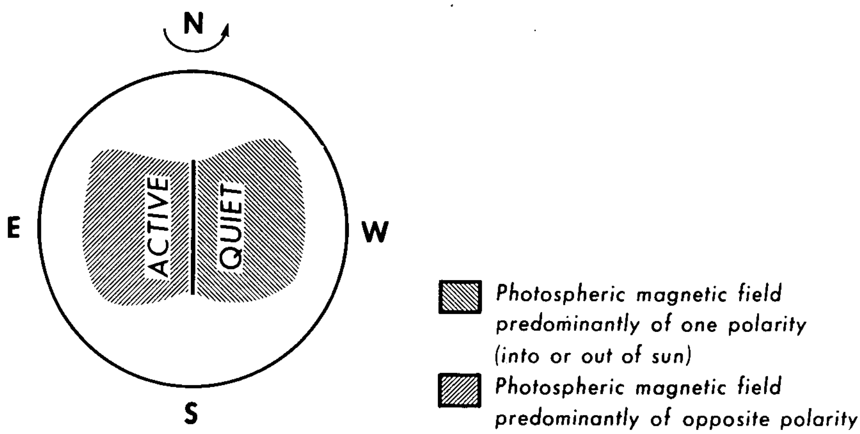

Fig. 5. Schematic of an average solar sector boundary. The boundary is approximately in the north-south direction over a wide range of latitude. The solar region to the west of the boundary is unusually quiet and the region to the east of the boundary is unusually active (from Wilcox, 1971).

of an average solar sector boundary (Wilcox, 1971) is shown in Figure 5. It appears that individual photospheric magnetic features such as bipolar magnetic regions display the shearing effects to be expected from differential rotation. However if one averages the observations over a few solar rotations a pattern similar to that shown in Figure 5 emerges.

The observed sectors may represent variations about a basic "dipole" configuration whose effects were first noticed in observations of polar geomagnetic fields by Olsen (1948). The link between the polar geomagnetic fields and a possible rotating solar magnetic "dipole" comes through a relationship between the polar geomagnetic fields and the polarity of the interplanetary magnetic fields discovered by Svalgaard (1968) and Mansurov (1969) and confirmed by Friis-Christensen et al. (1971), and by the link between interplanetary magnetic fields and photospheric magnetic fields demonstrated by Ness and Wilcox (1966). A schematic of the rotating solar magnetic "dipole" (Wilcox and Gonzalez, 1971) is shown in Figure 6.

In summary, we find an interesting variety of rotational properties in the photospheric and solar wind plasma and magnetic fields. In both the photosphere and in the interplanetary medium near the earth there is a tendency for the field patterns to rotate a few percent faster than the plasma patterns. The fields and

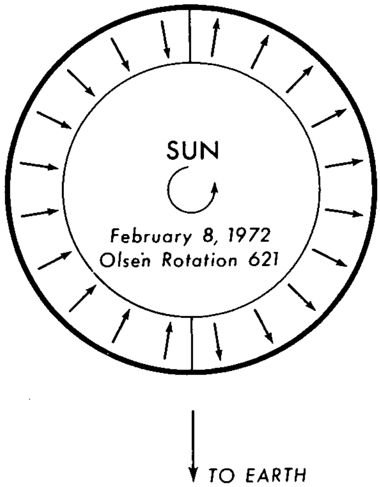

Fig. 6. Schematic of the rotating solar magnetic "dipole" (from Wilcox and Gonzalez, 1971).

plasmas show variability in their rotational properties on time scales of days or months, but averages over a few years tend to become much less variable, as shown by the results for long-lived sunspots, and by the rotating solar magnetic "dipole".

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